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LASER PEENING OF ALLOY 600 TO IMPROVE INTERGRANULAR STRESS CORROSION CRACKING RESISTANCE IN POWER PLANTS*

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ABSTRACT

Laser peening is an emerging modern process that impresses a compressive stress into the surface of metals or alloys. This treatment can reduce the rate of intergranular stress corrosion cracking and fatigue cracking in structural metals or Alloy 600 needed for nuclear power plants.

INTRODUCTION

Laser peening very effectively converts residual tensile stresses in metals to strong and relatively deep compressive stress [1]. Residual compressive stress depths reaching 20% of the part thickness have been achieved [2]. Laser peening could also be used to form thick metal or alloys into precise shapes without yielding, leaving their surfaces in a crack-resistant compressive state. Recent experiments indicate that laser peening virtually eliminates the occurrence of intergranular stress corrosion cracking and crack-growth in Alloy 600 base material and weldment.

In these report, we briefly review recent laser peening and intergranular stress corrosion cracking experiment performed on Alloy 600 coupons and discuss possible applications for electric power plants.

NOMENCLATURE

Laser peening, intergranular stress corrosion cracking, fatigue failure

Laser Peening Reduces Inter-Granular Stress Corrosion Cracking (IGSCC) in Alloy 600

A series of experiments were performed jointly by scientists from both EPRI and LLNL to determine if laser peening could be used to stop IGSCC in Alloy 600 base material and weldment. The primary objective is to evaluate if the PWR problem with cracking in the reactor lid around the control rod penetration could be mitigated using laser peening. Our goal is to process both new parts and re-work of the service parts.

During the course of this work, Alloy 600 base material and weldment (with an IN-182 weld) were supplied by EPRI. Laser peening and room temperature IGSCC tests were performed by LLNL. Laser peening was performed on the top and side surfaces of the U-bends with high-energy laser pulses (18 nanosecond pulse duration) at an irradiance of 10 GW/cm^2 and 200% coverage. Final examination of the IGSCC test coupons were performed by both institutes using visual and light microscopy in sensitized U-bends was performed in a dilute sodium thiosulfate solution (0.1 M at room temperature and pH of 3). It is well known [3] that IGSCC of chromium-depleted Alloy 600 occurs rapidly in sulfur, SO_2 or HSO_3^- environment (Figure 1).

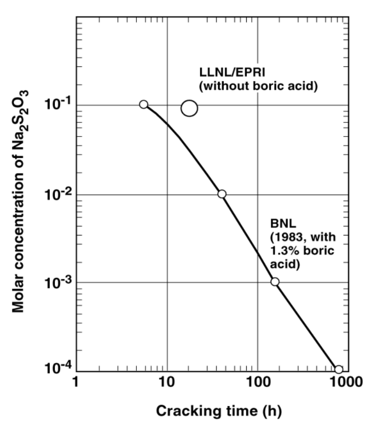

Figure 1, Measured IGSCC rate of Alloy 600 in sodium thiosulfate solution at room temperature

IGSCC testing of laser–peened Alloy 600 base material

Room temperature IGSCC tests were performed for Alloy 600 U-bend coupons in four conditions: unpeened, pre-cracked and unpeened, pre-cracked and laser-peened and, laser peened. Hairline cracks developed on the outer surface of unpeened coupons after one day in the thiosulfate solution. Cracks propagate quickly toward the inner surface with continue exposure (Figure 2). However, no crack was observed on the laser peened-coupon even after weeks of exposure.

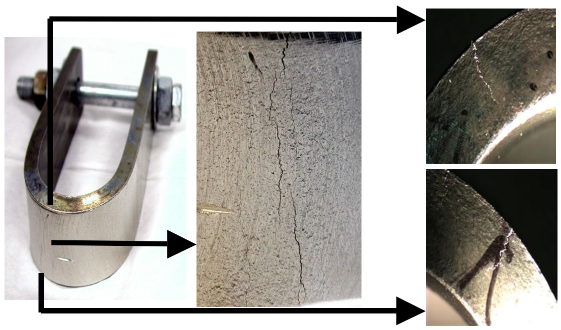

Figure 2, Hairline cracks developed on the surface of un-peened Alloy 600 coupons

Laser peening retarded IGSCC on pre-cracked U-bends. In this test, we performed laser pening on half of the stressed region of a pre-cracked coupon (figure 3). After immerse the pre-cracked coupon in room temperature thiosulfate solution, the crack located in the unpeened region was found to grow extensively while crack growth in the peeneed area appeared to be stopped completely. Cracking also appears to be tighter and shallower on the laser peened section (Figure 4).

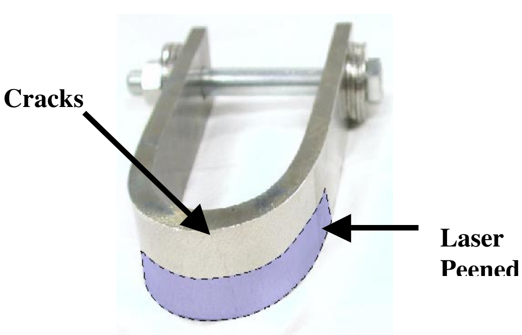

Figure 3, Laser peening of pre-cracked coupon

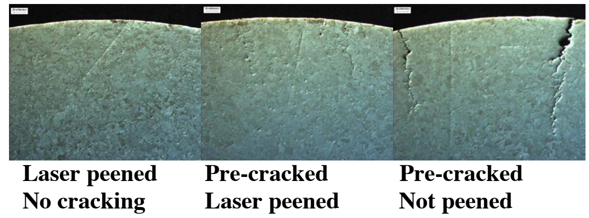

Figure 4, Laser peening stops crack initiation and growth in Alloy 600

IGSCC testing of laser-peened Alloy 600 weldment

Room temperature IGSCC tests were also performed for Alloy 600 welded U-bends in three conditions: as-received (with no peening), sensitized (with no peening) and sensitized (with laser-peening). Without laser peening, the as-received coupon cracked within two days while the sensitized one cracked after immersion in the thiosulfate solution for one day. Both U-bends cracked near the center of the weld beads. Half of the second sensitized U-bend was peened on the top and side surfaces with an irradiance of 10 GW/cm^2 and 200% coverage (similar to the pattern shown in Figure 3). Following the peening, the fixture bolt was tightened, further stressing the outer side of the U-bend. The unpeened half of the specimen developed hairline cracks after two days of exposure in thiosulfate solution, while no cracks were observed on the laser peened surface. Cracks growing from the unpeened side appear to stop prior to reaching the laser peened area (Figure 5).

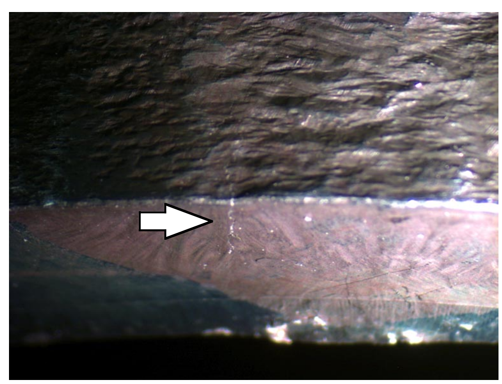

Figure 5, Laser peening stop IGSCC in welds. Crack observed at the un-peened region.

Laser Peening Retards Stress-Induced Corrosion Cracking of Stainless Steel

Test treatment of the laser processing also show it to be very effective in reducing corrosion and eliminating stress corrosion cracking in stainless steel [2]. During an accelerated stress corrosion cracking experiment in an aqueous solution of $MgCl_2$ at high temperature, we evaluated the effectiveness of laser peening to improve stress corrosion cracking resistance in type 304 stainless steel plates under normal weld-stress conditions. Figure 6 shows how the laser peening process reduces corrosion and stops stress corrosion cracking. The photo shows the results of a test on stainless steel type 316 where two sections of metal are welded together; the area on the left was laser peened and the area on the right was not. The surface was subjected to a highly corrosive environment of a 40% solution of boiling magnesium chloride.

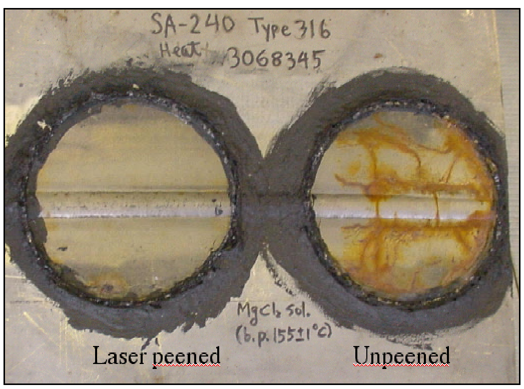

Figure 6, Laser peening retards SCC and overall corrosion in stainless steel 316

The unpeened area has several critical cracks running transversely through the welded section, and the test area has a highly corroded surface appearance. In contrast, the laser-peened area is free of stress corrosion cracks and rust. The application of laser peening is clearly making a significant improvement to the corrosion lifetime of the stainless type 316 metal.

In another convincing test, a welded section of 1-inch-thick stainless steel is peened in selected areas and then subjected to the harsh magnesium chloride environment. As seen in Figure 7, a stress corrosion crack, extending through the entire one-inch thickness of the

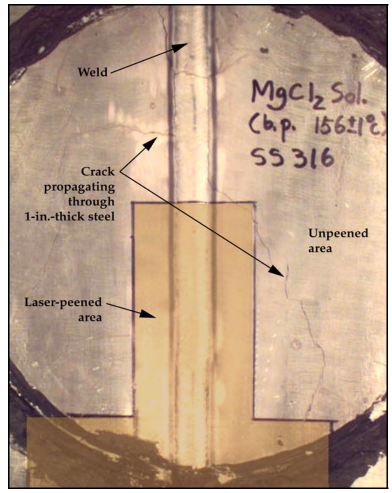

Figure 7. Laser peening significantly reduces stress corrosion cracking in welded 316 stainless steel.

material began to run longitudinally along the weld (along the right-hand side). However, when it encountered the laser-peened area, the compressive stress imparted to the surface effectively prevented the crack from propagating into the laser-peened area. The crack made continuing through unpeened area and eventually was arrested when it encountered the larger laser-peened area. The peening of the surface has clearly demonstrated a dramatic effect on the crack resistance of the stainless steel.

For the Department of Energy's Yucca Mountain Nuclear Waste Disposal Program, stress corrosion cracking is a primary concern in the design of the storage canisters since residual tensile stresses will be left behind by the closure weld. Alloy 22 is a nickel-based stainless steel that is particularly resistant to corrosion; however, there is a chance that stress corrosion cracking could develop giving the right environmental conditions. These canisters, which will be buried in Yucca Mountain, Nevada, need to remain intact for 10,000 years. After the canisters are loaded with radioactive waste, the lids are welded on. Stress corrosion cracking of the outer barrier lid weld has been identified as a critical failure point. Laser peening is a leading candidate to convert the residual weld stress from tensile to compressive, eliminating stress corrosion cracking on storage canisters.

Laser Peening Reduces Fatigue Failure in High Value Engine Fan Blades

Laser peening imparts a compressive residual stress to metal surfaces. With a compressive residual stress effectively pushing the atoms on the metal surface together, small surface cracks and flaws that could easily grow into larger destructive cracks are prevented from growing. This arrest of crack growth results in a significant enhanced lifetime against fatigue failure [1].

Tests on structural aluminum components under heavy load are showing 10- to 15-times lifetime improvements. As shown in Figure 8, recent fatigue tests on 6061 T6 aluminum under various stress load conditions show more than 50 times improvement in fatigue lifetime for structural aluminum test plates when compared to unpeened (control) components and 10 times improvement when compared to conventionally shot-peened components. Shot peening is widely used in industry to improve lifetime and resist corrosion. However, the residual stress imparted by shot peening is not nearly as deep as that achieved with laser peening, and consequently, laser peening provides a much greater lifetime improvement. This lifetime extension can have dramatic importance for the performance and reliability of field systems and an even greater effect on the maintenance costs to keep field systems operating.

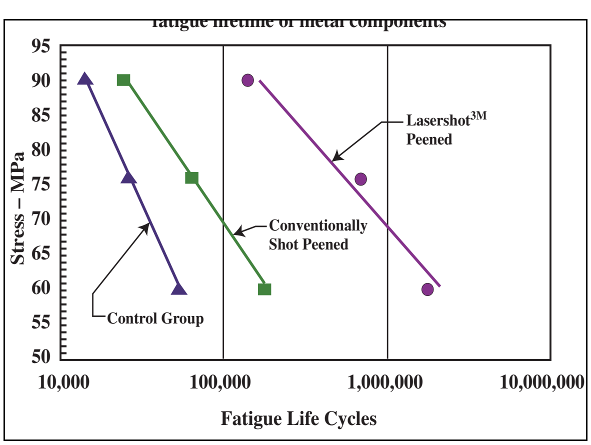

Figure 8. Laser peening significantly extends the fatigue lifetime of metal components.

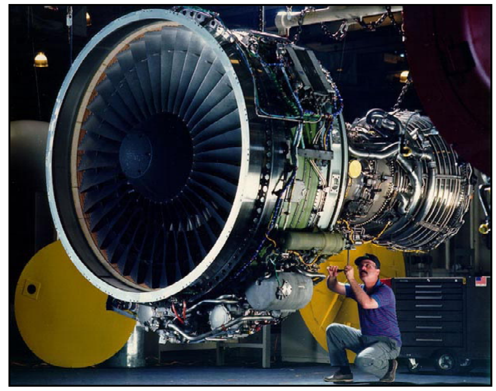

Figure 9. Production laser peening has arrived. It will increase the lifetime of parts, improving reliability and safety.

Laser peening is already having an important impact in preventing the failure of jet engine fan blades. The high-stress and high-cycle loading of these components has led to failures. Laser peening was introduced this past year into commercial production by industry to eliminate fatigue failure in high value commercial jet engine fan blades. In rigorous tests of laser peening, jet engine fan blades that used to develop fatigue failure cracks after 500 flights are now able to achieve 10,000 flight operations without failure.

Led initially by the U.S. Air Force, research also showed that laser treatment of the leading edge of blades against foreign object debris damage significantly extends the fatigue lifetime and allows even a highly damaged but laser-peened blade to have better fatigue lifetime than unpeened new blade. An even greater-magnitude application has been the treatment of wide cord fan blades for commercial engines to prevent fretting fatigue failure.

We anticipate that laser peening will also significantly improve the service lifetime of fan blades, turning gears and rotors used in fossil and nuclear electric power plant's steam turbines.

Laser peening is a Developed Process Enhancing Fatigue Lifetime and Safety of Fossil and Nuclear Power Plants

Laser peening was introduced into commercial production by industry in May 2002.

The process was developed, tested, and certified by the Federal Aviation Administration and then immediately brought into production to solve an important fatigue failure problem in high-value commercial jet engine fan blades and discs. Since initial deployment, multiple applications and aircraft worth billions of dollars are now in service with laser-peened parts—saving millions of dollars per month in aircraft maintenance costs and millions more in parts replacement costs, all the while greatly enhancing safety. Laser peening is also an emerging surface treatment technology that has recently been identified by DOE as an effective tool for mitigating tensile residual stresses in the storage canisters.

For electric power industries, laser peening could be used to eliminate primary water stress corrosion of welds around rod penetration in pressurized water reactors (PWRs). Laser peening of fan blades could also significantly improve the service lifetime of steam generator turbines. The electric power industry can now apply the laser peening technology to improve the safety, reliability, and operational life of the next generation fossil and nuclear power plants so that they will have longer service life and lower operating cost.

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